

ADAPTATION IN ISOLATED COLD SPOTS

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Systematic studies of thermal adaptation have been made almost entirely with areas of several square centimeters of skin tissue or larger.¹ Comparatively little is to be found in the literature concerning adaptation in single temperature spots. Yet if thermal sensitivity is assumed to be punctiform in nature, the single temperature spot would seem to be the logical starting point. This is particularly true because adaptation effects have played such a critical rôle in the development of theories of temperature sensitivity.

In areas of any considerable size, adaptation is generally found to be slow and incomplete; but is it safe to assume that this will be true with a single temperature spot? There are hints in the literature that such may not be the case. Many investigators have noted that stimulation of a temperature spot seems to depress its sensitivity rather rapidly. In mapping experiments, it is the traditional caution to avoid stimulating the same spot repeatedly.² A number of additional observations are to be found in the

* Accepted for publication August 7, 1935. From the Psychological Laboratory of the University of Michigan.

¹ An excellent bibliography of the studies of thermal adaptation prior to 1921 will be found in Elof Gertz, *Psychophysische Untersuchungen über die Adaptation im Gebiet der Temperatursinne und über ihren Einfluss auf die Reiz- und Unterschiedsschwellen*, *Zsch. f. Sinnesphysiol.*, 52, 1921, 1-51, 105-156. Important studies since then are: Erich Hummel, *Die Veränderung des Systemes der Temperaturempfindungen durch die Adaptation*, *Arch. f. d. ges. Psychol.*, 57, 1926, 305-394; Helmut Hahn, *Die psycho-physischen Konstanten und Variablen des Temperatursinnes*, *Zsch. f. Sinnesphysiol.*, 60, 1930, 162-232; Solomon Aronoff and K. M. Dallenbach, *Adaptation of warm spots under continuous and intermittent stimulation*, this JOURNAL, 48, 1936, 485-490; H. A. Levine and K. M. Dallenbach, *Adaptation of cold spots under continuous and intermittent stimulation*, *idem*, 490-497.

² Cf. M. B. Drury and K. M. Dallenbach, *The response of cold spots under successive stimulation*, this JOURNAL, 43, 1931, 490-496; and also R. H. Earhart and K. M. Dallenbach, *The response of warm spots under successive stimulation*, *ibid.*, 45, 1933, 722-729.



works of Goldscheider. He notes that complete disappearance of sensation may result from continuous or intermittent stimulation.³ The extent and duration of the ensuing depression depend upon the intensity and dura-

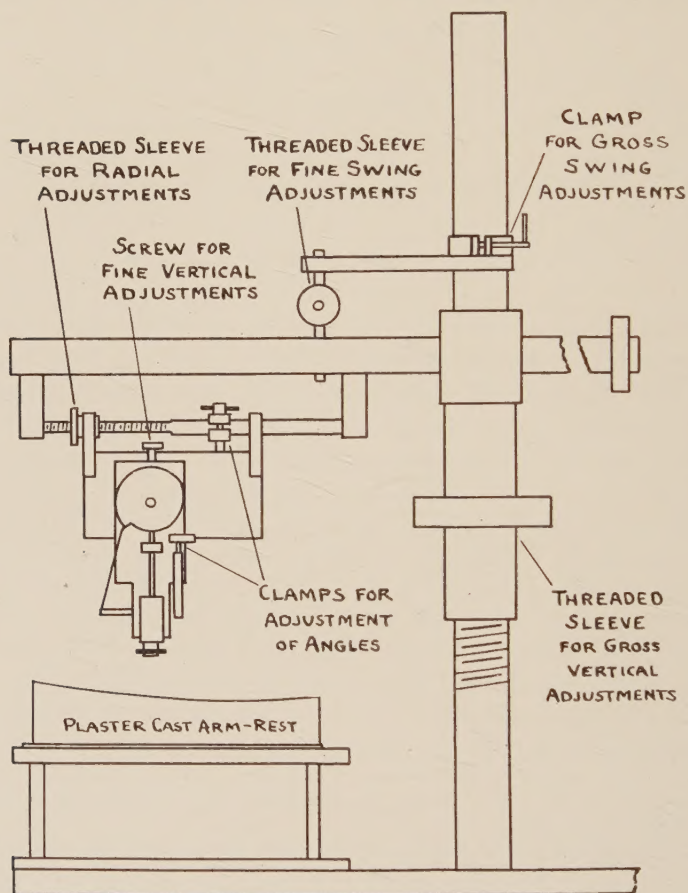


FIG. 1. MAIN APPARATUS

tion of the stimulus.⁴ Recovery is relatively slow, but the originally most sensitive spots show the most rapid recovery.⁵ Warming the skin does not hasten recovery.⁶ Unfortunately, all of these are recorded merely as qualita-

³ Alfred Goldscheider, *Gesammelte Abhandlungen*, 1898, 142 f.

⁴ Goldscheider, *Temperatursinn des Menschen*, in *Bethe's Handbuch der normalen und pathologischen Physiologie*, 11, 1926, 134 ff.

⁵ Goldscheider, *Gesammelte Abhandlungen*, 1898, 152.

⁶ *Ibid.*, 143.

tive statements, without specific figures which could be used as a basis for comparison with the usual results for larger areas.

In the following study, adaptation effects in single cold spots have been studied systematically. Furthermore, a technique has been used whereby

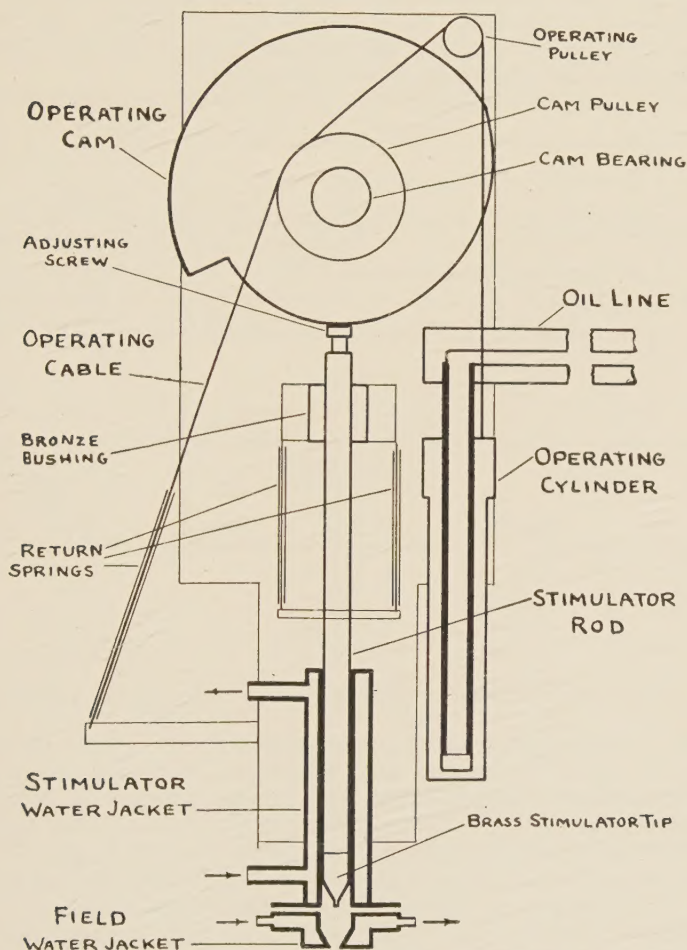


FIG. 2. DETAIL OF THE MECHANISM OF THE STIMULATOR-FIELD

simultaneous tactual stimulation is excluded, since it is believed that touch may complicate and confuse accurate thermal discrimination.

METHOD AND PROCEDURE

Apparatus. The apparatus used in this investigation is structurally complex, but functionally rather simple. It provides a means of surrounding a cold spot with a

field 16 mm. in diam. and stimulating it with a metal tip 1.25 mm. in diam. The temperatures of the field and of the stimulator-tip may be varied and measured independently. The stimulator-rod is moved down by a cam so that the tip comes just flush with the surface of the field disk. Hence, there is normally no distortion of the skin and no tactual stimulation to distract *O.*

Fig. 1 shows the main apparatus and the method of supporting and controlling the stimulator-field mechanism. The mechanism may be clamped at any desired angle so that the surface of the field disk lies tangent to the skin. It may be adjusted both horizontally and vertically to the necessary position.

Fig. 2 is a simplified drawing of the mechanism of the stimulator-field. When

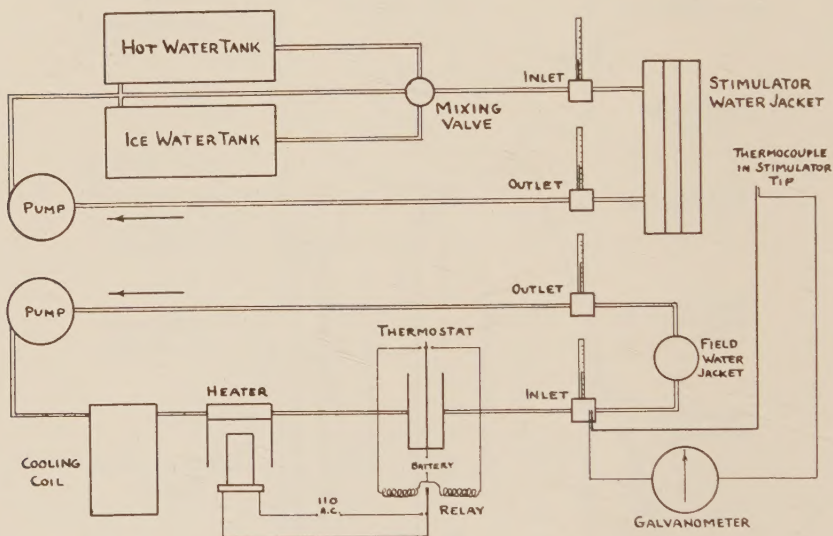


FIG. 3. SCHEMATIC DIAGRAM OF TEMPERATURE CONTROL AND MEASUREMENT

pressure is applied through the oil line, the operating cylinder moves downward, turning the cam via the operating cable. At the other end of the oil line is the operating mechanism. When the experimenter depresses a handle, this mechanism: (a) sounds a warning buzzer; (b) introduces a delay of 2 sec. by means of a dash-pot timer; (c) then applies pressure to the oil line by a system of weights.

Fig. 3 is a schematic diagram of the system of temperature control and measurement. The field-temperature may be: (a) maintained thermostatically at 33°C. ; (b) gradually raised by manual control of the heater; (c) gradually lowered by manual control of the cooling coil. The field-temperature is measured by inlet and outlet thermometers; in practice only the inlet temperature being recorded regularly.

The stimulator-temperature is controlled by varying the temperature of the water pumped through the stimulator jacket. The mixing valve permits either hot water or ice water to be mixed with the water flowing through the system. The temperature of the stimulator-tip is measured by a thermocouple-galvanometer system. One junction of a constantan-copper thermocouple is in the stimulator-tip; the other

junction is in the jacket for the field inlet thermometer. The galvanometer scale is calibrated to read degrees C. directly. Inlet and outlet thermometers provide a check on the galvanometer readings. Reaction-times are measured by the typical break-and-break operation of a synchronous motor chronoscope.

Mapping and marking. At the beginning of an experimental series, several sensitive cold spots were located and marked with a drop of ink. A ring 16 mm. in diam. was then drawn around each spot, using a bow-pen with a mixture of silver nitrate solution and indelible ink. Since the same spots were worked on repeatedly for several weeks or months, these rings required renewal from time to time.

Experimental routine. The typical procedure in securing data on a cold spot may be outlined as follows.

(1) *O*'s left arm was supported in a half plaster cast (made individually for each *O*), with the volar surface approximately horizontal. The mechanism was then adjusted so that the field disk coincided with a marked ring and pressed lightly and evenly on the skin. The spot was then stimulated once with a temperature of about 12° C. Readjustment of the position of the mechanism was made in case this exploratory stimulus did not give the normal intensity of sensation.

TABLE I
TYPICAL DETAIL RECORD ILLUSTRATING THE PROCESS OF DETERMINING THE NORMAL LIMINAL TEMPERATURE

Stimulus- temperature	Reaction-time (millisec.)	Report
28.0°	—	0
24.3°	468	1
25.9°	451	1—
28.0°	—	0
26.6°	476	1—
27.7°	—	0
27.2°	—	0

(2) After a rest of 5 min., the normal liminal temperature⁷ was determined by stimulating with a series of temperatures just above and below this level, the field temperature being maintained thermostatically at 33° C. *O* reacted when he felt any cold sensation and reported its intensity in terms of the following code: 3 for strong cold; 2 for moderate cold; 1 for weak cold; 0 for no sensation. Several *O*s introduced intermediate degrees of their own accord. The record in Table I is a typical example of the procedure of determining the normal liminal temperature, in this case approximately 26.5° C.

(3) The conditions to be tested were then introduced. In general, these were continuous or intermittent stimulation at 10°, 20° and 40° to 46° C.; or changes in the field temperature. Sometimes two or more conditions could be tested in the same run. The effects were studied principally by following the course of the liminal temperature, stimulating at 30-sec. intervals. The accuracy of such a method, of course, depends upon how well the experimenter is able to select testing temperatures

⁷ To avoid involved phraseology, the term 'liminal temperature' is used to designate the highest temperature of the stimulator which was effective in eliciting a cold sensation.

which lie alternately on each side of the liminal temperature. Fortunately, in all these experiments the effects were usually so clear-cut that the general course could be plainly indicated by this method.

Limitations of the method. In general, it is believed that the procedure outlined was adequate for the problem. It is desired, however, that the limitations of the method be clearly appreciated. The most important of these are:

(1) *Errors in re-location.* The marked ring seldom remained a true circle from day to day, but was usually distorted into various elliptical shapes.⁸ Hence, there is no assurance that a given spot was stimulated in exactly the same way from period to period. In practice, a purely empirical criterion was used: the exploratory stimulus must give rise to the normal clear cold sensation characteristic of the particular spot.

(2) *Limits of temperature measurement.* Allowing for the temporal lag of the measuring devices and the errors of calibration and reading, it is believed that the temperatures of the stimulator and field as given are correct within plus or minus one degree. Any errors of this size would not affect the general implications of the results; but might be important in the consideration of absolute values; for example, the maximum temperatures to give a cold sensation with normal and elevated field temperatures.

(3) *Limits of time control.* The duration of stimulation was determined by the length of time *E* held down the operating lever, and was necessarily subject to some variation. This is chiefly important in short durations, as in testing for the liminal temperature and in intermittent stimulation, where the stimulator-tip was in contact with the skin for one second or less. With stimulus-durations of several seconds or more, the variations would be of little consequence.

RESULTS

With the apparatus and procedure previously described, complete or partial data were obtained on some 30 cold spots on the volar surface, left forearm, of 6 *Os*.⁹ All were young men students, psychologically naïve as far as a knowledge of the facts of temperature sensitivity was concerned. They were kept in ignorance of the purpose of the problem and the trend of the results. The experiments were performed between March 20 and May 21, 1935, at different times of day and under a variety of preceding environmental conditions. The room temperature was usually 22-23° and the typical test period one hour in length.

(A) *With field at 33° C.* (1) *Normal limen.* The solid squares in Fig. 4 indicate the normal liminal temperatures on various occasions for 20 different cold spots on 6 *Os*. Each vertical column contains the data for one

⁸ For similar volumetric changes see K. M. Dallenbach, The temperature spots and end-organs, this JOURNAL, 39, 1927, 407 f.

⁹ Our thanks are due Miss Margaret Ives and Mr. Charles Irwin for acting as *O* and *E* respectively in the preliminary experiments, and to Messrs. Bolitho, Clark, Malewitz, Richter, Riker, and Sajkowski for acting as *Os* in the main experiments. Our thanks are also due Professors Carl R. Brown and B. D. Thuma for their aid in constructing the apparatus and in developing the method.

cold spot, the letters and digits at the top indicating the *O* and identification number of the spot. There are definite indications of individual differences among cold spots and among the *O*s, which may account for the discrepancies in the results reported in the earlier literature. Goldscheider,¹⁰ for instance, found some cold spots on his own left forearm which responded to 32°, and more responding to 30.5°. Siebrand,¹¹ on the con-

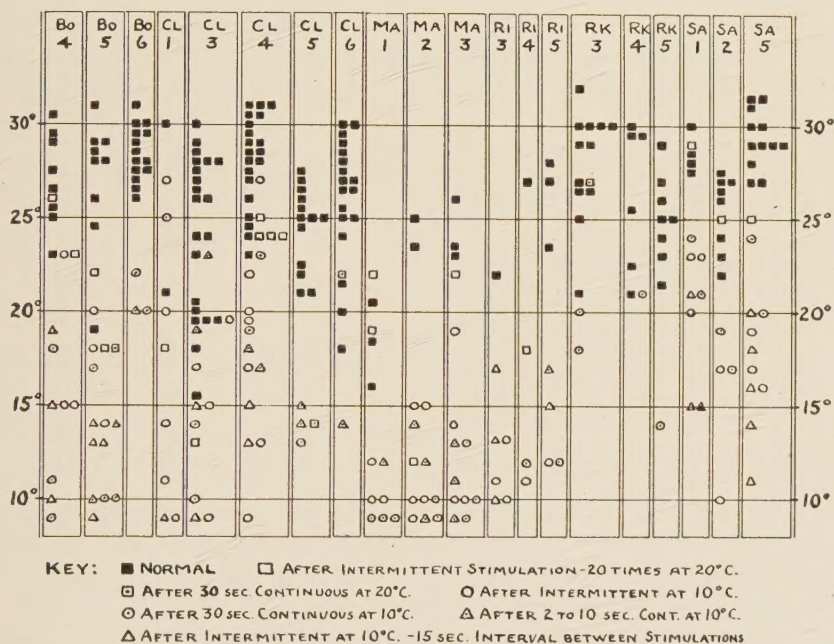


FIG. 4. NORMAL AND DEPRESSED LIMINAL TEMPERATURES
 (Each column gives the data for one cold spot.)

trary, found in a similar area on his *O* no spots with a normal liminal temperature above 29.5° and the majority in the range of 27° to 28°. Apparently the sensitivity of some single cold spots is nearly as great as that of larger areas; although Goldscheider has shown that an area of several square centimeters will respond to a temperature which will not excite any of the individual spots within it.¹²

¹⁰ Goldscheider, Beiträge zur Lehre von der Hautsensibilität, *Zsch. f. klin. Med.*, 74, 1921, 274.

¹¹ —, Siebrand, Untersuchungen über den Kältesinn, *Zsch. f. Sinnesphysiol.*, 45, 1911, 208.

¹² Goldscheider, *op. cit.*, *Zsch. f. klin. Med.*, 74, 1912, 280.

Individual differences in variability among the different cold spots can also be noted. The liminal temperatures determined in the same spot on various occasions are closely grouped in some spots (as *Bo-6* and *Sa-5*) and are quite scattered in others (as *Cl-3* and *Cl-6*).

(2) *Depression by low temperatures.* In general, the after-effect of stimulation by low temperatures, either intermittent or continuous, was a long-lasting depression of the liminal temperature. The symbols in Fig. 4 show these depressed levels in accordance with the key at the bottom of the chart. As these results indicate, the effects of different types of stimulation varied considerably from spot to spot, and in the same spot from

TABLE II
AVERAGES OF NORMAL AND DEPRESSED LIMINAL TEMPERATURES, OBTAINED
BY COMBINING RESULTS FOR ALL O_3

Condition	Mean	A. D.	Range	No. cases
Normal	26.4°	2.7°	15½-32°	167
After 20 intermittent brief stimulations at 20°, 30-sec. intervals	21.7°	3.2°	12-29°	18
After 30-sec. continuous stimulation at 20°	20.3°	4.3°	14-27°	4
After 20 intermittent brief stimulations at 10°, 30-sec. intervals	15.3°	3.9°	9-27°	47
After 20 intermittent brief stimulations at 10°, 15-sec. intervals	14.1°	2.6°	9-21°	24
After 2-10 sec. continuous stimulation at 10°	14.5°	3.0°	9-23°	18
After 30-sec. continuous stimulation at 10°	15.3°	5.0°	9-25°	34

period to period. These facts must be kept in mind when considering the averages in Table II which were obtained by combining the data for all 20 spots in order to give a rough perspective of the general magnitude of the depression. The effect of the stimulus varies with:

(a) *The spot tested.* For example, witness the drastic effects on *Ma-2*, compared with the mild depression in *Sa-1*.

(b) *The stimulating temperature.* The depression after 10° is definitely greater than that after 20°.

(c) *The interval between stimulations.* Apparently intermittent stimulation at 15-sec. intervals produced somewhat greater depression than intermittent stimulation at 30-sec. intervals. This is best shown by considering individual spots in which a number of instances of both types are available (as *Bo-5* and *Sa-5*).

(d) *The duration of stimulation.* Apparently this is effective only within certain limits, since durations of 30 sec. produced only slightly greater depressions than durations of 2-10 sec., and these only on weaker spots.

The symbols in Fig. 4 indicate in each case the lowest level of the depression following stimulation by low temperatures. The course of the ensuing recovery was determined only under the conditions of testing every 30 sec. to determine the liminal temperature. Under these circum-

stances, recovery was found to be relatively slow—not faster than 1° per min., and usually much slower. This is partially an artifact. Every stimulation would tend to produce its own depressing effect, thus artificially delaying recovery. Hence, when the depression was extreme and testing temperatures correspondingly low, frequently no recovery at all was evidenced. With complete rest, the rate of recovery would undoubtedly be higher, but systematic determinations of this kind were not undertaken, because of the great amount of time such a process would consume.

Goldscheider holds that the depression following stimulation is preceded by a brief period of hyper-sensitivity.¹³ Possibly because of a difference in

TABLE III
TYPICAL RECORD FROM A 'FADING' SPOT

Order	Stim.-temp.	Reaction-time (Millisec.)	Report	Order	Stim.-temp.	Reaction-time (Millisec.)	Report
(1)	20.4	490	I	(10)	17.9	—	o
(2)	23.9	—	o	(11)	17.7	—	o
(3)	20.6	—	o	(12)	17.1	583	I
(4)	19.6	—	o	(13)	16.8	—	o
(5)	17.7	461	I	(14)	16.4	—	o
(6)	18.3	520	I	(15)	14.4	—	o
(7)	18.0	538	I	(16)	12.3	—	o
(8)	18.3	—	o	(17)	10.5	—	o
(9)	18.0	537	I				

technique, the present study does not confirm this finding. Tests made 30 sec., even 15 sec., after cessation of stimulation showed only marked depression.

(3) 'Fading.' The depressive effects of approximately liminal (and possibly even sub-liminal) stimulation are illustrated by the phenomenon of 'fading.' This term is used to describe a swift downward trend of the liminal temperature under the mild stimulation incidental to determining the normal level. One such instance is shown in Table III. Sometimes the plunge was even more rapid than this. Frequently, within half a dozen stimulations at 30-sec. intervals, such a spot would fail to respond to 10° , although the response to the original exploratory stimulus had been of quite normal intensity. 'Fading' was a frequent occurrence in some spots and was never observed in others. None of *Sa*'s spots ever showed it; whereas all of *R*'s faded consistently every time tested during the last three weeks of the experimental period.

In determining the liminal temperature, we are apparently dealing with a 'principle of uncertainty.' To find the liminal temperature, it is necessary

¹³ Goldscheider, *Temperatursinn des Menschen*, in *Bethe's Handbuch der normalen und pathologischen Physiologie*, 11, 1926, 134.

to stimulate the spot, but this stimulation in itself may cause a depression; hence uncertainty. Fortunately, in most spots, if the testing temperatures are kept close to the liminal level, this depressing effect seems to be slight.

TABLE IV
RESTORATIVE EFFECT OF HIGH TEMPERATURES

Columns A=Liminal temperature just before contact with high temperature.

Columns B=Liminal temperature after 1 min. contact with stimulator-tip at 40°-46°.

Columns C=Liminal temperature five minutes later.

O and spot	A	B	C	O and spot	A	B	C	O and spot	A	B	C
Bo-5	31°	32°	32°	Cl-6	27°	30°	29½°	Ri-6	10°	21½°	10°
Bo-5	32	32		Cl-6	20	29½	24	Ri-6	10	20	11
Bo-5	10	22	13	Cl-6	14	30½	30½	Ri-6	10	13	10
Bo-5	18	29	27	Cl-6	17	30½	29	Ri-6	10	20	11
Bo-5	18	26	22	Cl-6	15	25	16	Ri-6	10	21	11½
Bo-5	15	25	13	Cl-6	12	21½	11	Ri-6	10	19	11
Bo-5	13	14	11	Cl-6	11	26½	11				
Bo-5	19½	27	9	Cl-6	10	21½	10½	Rk-1	16	19	9½
Bo-5	10	22	11	Cl-6	9	20½	10				
				Cl-6	10½	20½	11	Rk-2	19	25½	23
Bo-6	21	29	26	Cl-6	11	26	11	Rk-2	23	28	23
Bo-6	23	29	26	Cl-6	10½	19½	10½				
Bo-6	13	25	20	Cl-6	11	19	11	Rk-3	18	31½	
				Cl-6	11	20½	11	Rk-3	23½	31½	
Cl-1	10	21	10	Cl-6	11	20½	11½	Rk-3	11	24	24
								Rk-3	10	19	10½
Cl-3	28½	30½	31	Ma-1	18½	19½	17				
Cl-3	27	31½						Rk-4	21	28	26½
Cl-3	31½	31½		Ma-2	14	11	11	Rk-4	10½	10½	
Cl-3	19½	25	25	Ma-2	14	25	22				
Cl-3	18	27	24	Ma-2	22	29½		Rk-5	14½	25½	20½
Cl-3	13	27½	24								
Cl-3	10	13	11	Ma-3	26	29	26	Sa-1	23	31	
				Ma-3	10	16	11½	Sa-1	24	31	
Cl-4	27	31	30	Ma-3	13	20½	16½				
Cl-4	30	31	31					Sa-2	17	27½	25
Cl-4	28	30	30	Ri-3	9	17	11	Sa-2	19	24½	
Cl-4	11	24½	11								
				Ri-4	12	27	10	Sa-5	24½	30½	30½
Cl-5	26	31	28					Sa-5	30½	31½	
Cl-5	25	27	27	Ri-5	17	28	26	Sa-5	20	30	30
Cl-5	27	28	28	Ri-5	12	28	19½				
Cl-5	15	22	17	Ri-5	10	15	10	Sa-7	19	28	26
Cl-5	13	23	16	Ri-5	10	16	10½				
Cl-5	10	20	19	Ri-5	10	18	10½				
Cl-5	12	23	11	Ri-5	10	19	10				
Cl-5	10	15		Ri-5	11	19	13				
Cl-5	10	20	11								

In many instances, it was possible to stimulate a dozen times or more with temperatures close to the limen, without affecting its level.

(4) *Restoration by high temperatures.* More striking than the depression by low temperatures, is the rapid restoration of the liminal temperature by one minute's contact with a stimulator tip at 40° to 46°. Table IV

shows the effects secured on various occasions in twenty-three different spots. Column A is the liminal temperature just before the high temperature was applied. Column B shows the corresponding liminal temperature after one minute's contact with a stimulator tip at 40° to 46° . Column C shows the liminal temperature 5 min. later.

Notice that even an extremely depressed limen can be restored temporarily to somewhere near its normal level. Where the depression has not been too great, this restored level may be reasonably well maintained. After extreme depression, however, even mild stimulation typically causes a slump, and within 5 min. the limen is back at its depression level. This secondary

TABLE V

DURATION OF THE SENSATION WITH CONTINUOUS STIMULATION OF A SINGLE COLD SPOT AT A CONSTANT TEMPERATURE

Duration	No. cases	Percentage
Less than 2 sec.	20	21
From 2-4 sec.	53	57
From 4-6 sec.	10	11
Over 6 sec.	10	11

slump is particularly precipitate in spots restored after 'fading.' Yet the treatment proved singularly effective in almost every case, and became the standard method of resuscitating spots that had 'faded.'

(5) *Restoration by rest periods.* Following extreme depression, rest periods of 2-5 min. were sometimes introduced. After such a rest, the spot would usually respond—once, twice, rarely more—even to considerably higher temperatures. Then it was 'out' completely to the lowest testing temperatures available. This restoration was evidently more temporary than that brought about by high temperatures. The two seem, however, to have one point in common; in both cases, it is the liminal temperature of the spot that is restored and not its stability. Rest periods longer than 5 min. were not tested.

(6) *Duration of cold sensations.* Tests were made with continuous stimulation at 10° , 15° , 20° , and 25° , to determine the time needed to reach complete thermal indifference with constant temperature. In these tests, the Os were instructed to release the reaction-key when the sensation died out, thus measuring the elapsed time from the instant of contact of the stimulator-tip. In these discriminations, the absence of simultaneous tactual stimulation was a distinct aid; for, when the cold sensation died out, there was nothing left. The results showed a surprising agreement. At all temperatures and for all Os combined, the durations of the cold sensations were distributed as shown in Table V. (The disappearance of the cold sensation was not caused by a warming-up of the stimulator-tip, since the

temperature of this never rose more than a degree or two during the entire period of contact.) In three-quarters of the cases, complete adaptation occurred in less than 4 sec. Only in the single instance of *Sa* were durations longer than 10 sec. ever experienced, and many of his were shorter than 4 sec. All of the times are so short that it is impossible to say whether there is a definite relation between the adapting temperature and the time needed to reach complete thermal indifference, such as has been found with larger areas.

The chief point of interest here is that durations averaging less than 4 sec. are of a totally different order of magnitude from those reported by Holm¹⁴ and Gertz¹⁵ with an area of about 5 sq. cm. Holm used a metal stimulator 5 cm. in diam., fastened to the abdomen and surrounded by a ring maintained at skin-neutral. Gertz repeated this experiment on the forearm, and also employed the scheme of anesthetizing a ring of skin around the stimulator to eliminate any effects from the spread of the stimulus. To reach complete thermal indifference, Holm found times varying from 210 sec. at 5°, to 72 sec. at 20°, to 31 sec. at 30°. The values given by Gertz are somewhat longer. With areas as large as the hand, various experimenters have found that complete thermal indifference is not reached in half an hour or more, except with temperatures close to that of the skin.

(7) *Reaction-time.* Since the measurement of reaction-time was a routine accompaniment of each stimulation, the entire series resulted in the accumulation of well over ten thousand measurements. A detailed presentation of these will be omitted and the essential findings summarized in the following statements.

(a) Every *O* tended to show a basic level of reaction-time, varying from about 300 millise. for the fastest *O* to about 600 millise. for the slowest. As might be expected, these reaction-times are much longer than those reported for stimulation of larger areas, which are from 150 to 200 millise.¹⁶

(b) Marked deviations of single reaction-times from the general level appear to be referable mainly to central factors. For example, with extremely weak sensations, very long reaction-times sometimes occurred. Frequently, *O* would then report that he had been slow to react because he was not sure at first that he had felt anything.

(c) There is absolutely no evidence, in these cold spots, of any clear-cut relation between the length of reaction-time and stimulus temperature. Table VI shows the averages of reaction-times at 10° and 20° for several spots. Every figure in the table is the mean of 20 to 100 individual measurements, taken in sets of twenty under comparable conditions. The differences between reaction-times at 10° and at

¹⁴ K. G. Holm, *Die Dauer der Temperaturempfindungen bei constanter Reiztemperatur*, *Skand. Arch. f. Physiol.*, 14, 1903, 245.

¹⁵ Gertz, *op. cit.*, *Zsch. f. Sinnesphysiol.*, 52, 1921, 22-25.

¹⁶ Goldscheider, *Gesammelte Abhandlungen*, 1898, 312-355; Friedrich Kiesow and Mario Ponzio, *Beobachtungen über die Reaktionszeiten der Temperaturempfindungen*, *Arch. f. d. ges. Psych.*, 16, 1910, 376-396; M. von Vintschgau and E. Steinach, *Zeitmessende Versuche über den Temperatur- und Drehsinn*, *Arch. f. d. ges. Physiol.*, 43, 1888, 152-194.

20° are negligible, except in the case of *Sa-5* where the value for 20° is the mean of only twenty readings and the discrepancy may be the result of chance variation.

There is certainly no indication in our results that reaction-times are consistently shorter at the lower temperature. This point is emphasized, because the length of reaction-time has been used by Bazett and McGlone to compute the depth of the thermal receptors, on the basis of the rate of temperature conduction through the skin.¹⁷ If any considerable portion of the reaction-time were required for conduction through the skin, on purely physical principles we should expect to find shorter reaction-times with steeper temperature gradients (lower temperatures). Such is clearly not the case; hence the validity of such computations must be questioned.¹⁸

TABLE VI
AVERAGE REACTION-TIMES AT 10° AND 20°
Av. reaction-time in millisecc.

O and Spot	at 10°	at 20°
<i>Bo-4</i>	439	409
<i>Bo-5</i>	485	501
<i>Cl-4</i>	390	395
<i>Ri-4</i>	302	304
<i>Sa-5</i>	477	398

(8) *Sensations at high temperatures.* As a by-product of the process of restoring depressed spots by contact with high temperatures, it was expected to learn something concerning the nature of paradoxical cold; but surprisingly, 'cold' was never reported by any of the 6 *O*s as the result of stimulation of cold spots by high temperatures. Out of 153 cases in which the stimulator-tip had a temperature of 41° to 46°, the reports were: 'Nothing,' 90 times; 'Hot,' 33 times; 'Warm,' 24 times; and 'Non-thermal,' 6 times. All equivocal instances, such as those in which the *O*s might have confused simple touch with warmth, are omitted.

It is significant that 'hot' and 'warm' were reported from stimulation of 13 different spots on 5 of the 6 *O*s. The remaining *O* reported either non-thermal sensations or nothing. When an *O* reported 'hot' or 'warm,' and the same stimu-

¹⁷ H. C. Bazett, B. McGlone, R. G. Williams and H. M. Lufkin, Sensation: I. Depth, distribution and probable identification in the prepuce of sensory end-organs concerned in sensations of temperature and touch; thermometric conductivity, *Arch. Neurol. & Psychiat.*, 27, 1932, 489-517.

¹⁸ Likewise questionable is the assigning of differences in cold and warm reaction-times to a difference in the depth of the cold and warm receptors. In some preliminary studies in which the writer acted as *O*, cold reaction-times averaging well under 300 millisecc. were secured. In the same area, was found one sensitive warm spot which was tested on several occasions. Reaction-times to temperatures between 38° and 46° averaged well over 900 millisecc., yet there was apparently no relation between reaction-time and stimulating temperature. Repeated attempts to obtain reaction-times to warm spots from our six regular *O*s proved unsuccessful.

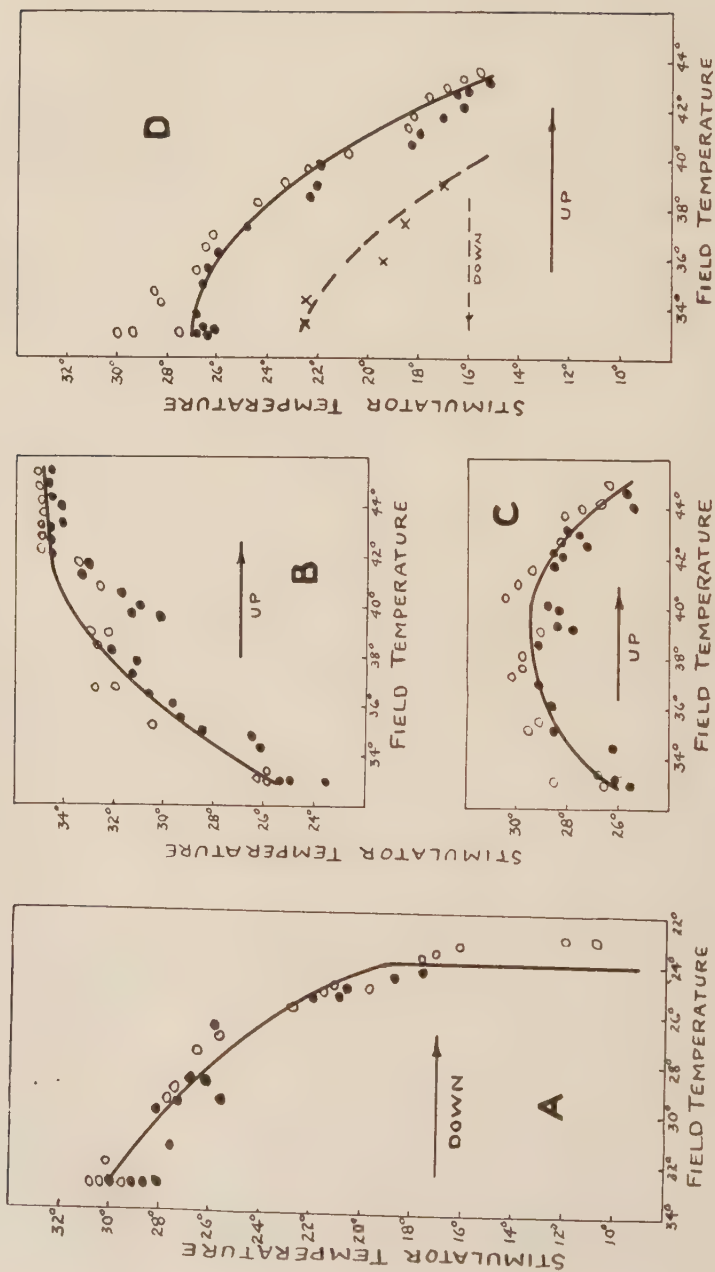


FIG. 5. TYPICAL DETAIL RECORDS WITH RAISED AND LOWERED FIELD-TEMPERATURES

lation was repeated at 30-sec. intervals, he typically felt nothing at all after the first time. Very rarely, a first report of 'hot' might be followed by a report of 'warm' on the second stimulation, and then 'nothing' on the ensuing stimulations.

It is not intended that such reports from psychologically naïve subjects should be taken as adequately descriptive. Yet every *O*, at some time, experienced some sensation at these higher temperatures; and that sensation was certainly not cold. Granting that the 'hot' and 'warm' reports may have resulted from stimulation of adjacent warm spots, the utter absence of paradoxical cold is still arresting.

The one difference in technique that is evident is the presence of the neutral field around the stimulator-tip. This would tend to minimize irradiation. The absence of simultaneous tactual stimulation can scarcely be a differential, because Altrutz succeeded in eliciting paradoxical cold by focusing the sun's rays on a cold spot with a lens.¹⁹

The reports of 'hot' and 'warm,' recall an almost forgotten study by Kiesow. Employing the usual metal stimulator, he aroused paradoxical cold repeatedly with temperatures between 38° and 40°. He says, "ich habe aber anderseits bei meinen Versuchspersonen kaum einen Kältepunkt gefunden, auf dem sich von einem gewissen Punkte an eine Wärmeempfindung beobachtet wurde. Dieser Punkt wurde bei 47° bis 50° C. bestimmt."²⁰ His description of procedure offers no explanation of why his results should have differed from those commonly obtained. In a later article on apparatus, he speaks of stimulating through holes in a sheet of gutta percha placed over the skin, but does not state whether this device was used in the earlier study.²¹ Such a protecting sheet might act similarly to the neutral field around the stimulator-tip in the present study.

Likewise interesting are the results obtained by Heiser, who used an elaborate apparatus for mapping warm spots on the foreheads of 33 *Js*. Although he employed temperatures as high as 47°, reports of 'cold' occurred so rarely that he does not include them in his tabulated results. In Heiser's apparatus, there was no neutral disk nor protecting sheet around the stimulator-tip which was 1.1 mm. in diam.; yet certainly paradoxical cold was a very rare phenomenon. In his summary, he says: "Though no cold stimuli were applied in this experiment, it is certain that some of the spots giving warmth sensation would also have given cold sensation, for in some areas as much as 70-90% of all the spots gave warmth sensation."²²

(B) *With varied field-temperatures*. All of the foregoing results were obtained with the field-temperature maintained thermostatically at 33°—or approximately skin-neutral. In the following experiments, the temperature of the field was gradually lowered or raised, and the course of the liminal temperature traced by testing at 30-sec. intervals.

(1) *Field-temperature gradually lowered*. The detail record shown in Fig. 5 A is typical of the results obtained when the field-temperature was

¹⁹ S. Altrutz, Studien auf dem Gebiete der Temperatursinne, *Skand. Arch. f. Physiol.*, 7, 1897, 333.

²⁰ Friedrich Kiesow, Untersuchungen über Temperaturempfindungen, *Philos. Stud.*, 11, 1895, 145.

²¹ Kiesow, Ein einfacher Apparat zur Bestimmung der Empfindlichkeit von Temperaturpunkten, *Philos. Stud.*, 14, 1898, 589-590.

²² Florian Heiser, Stimulus-temperature and thermal sensation, *Arch. Psychol.*, 21, 1932, (no. 138), 81.

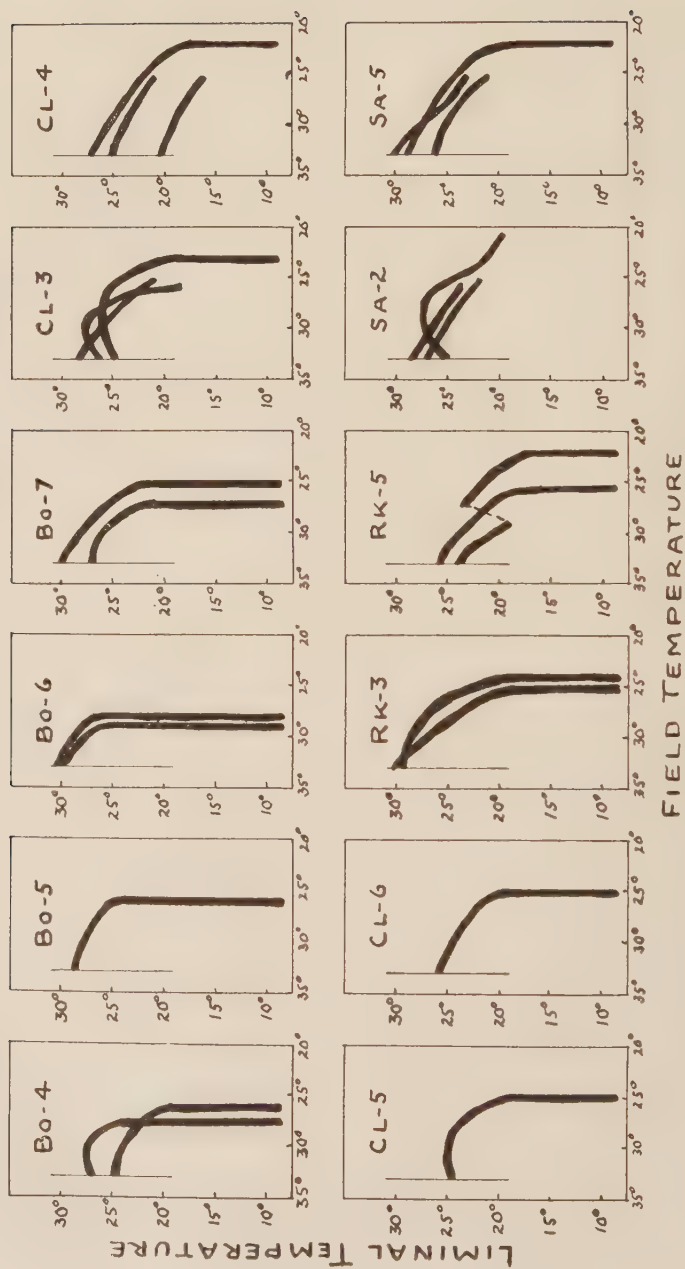


FIG. 6. EFFECTS OF LOWERED FIELD-TEMPERATURE ON DIFFERENT COLD SPOTS

slowly reduced. As the field-temperature drops, the liminal temperature holds its own, relatively, for several degrees. Then quite suddenly, it plunges sharply downward until the spot will no longer respond to the lowest testing temperatures available. Fig. 6 shows the results for a number of different cold spots, each curve being plotted in a manner similar to that shown in Fig. 5 A.

There is an indication that the break occurs at a certain critical level of field-temperature, which is never far below the normal liminal temperature and can scarcely be called excessively low in any case. It is believed that the apparent 'critical level' is genuine. For example, it was found that a stable liminal temperature could be determined with the field at about 28° —only to have the spot fail completely in a few stimulations when the field reached 25° .

What happens at this critical field-temperature in all spots appears to be very similar to what occurs at normal field-temperature in 'fading' spots. For the first test or two, the liminal temperature may be quite high, but it does not stand up under repeated stimulation. Succeeding tests indicate a lower and lower liminal level, until the spot is 'out' even for 10° . Just as with 'fading' spots, the liminal level may be restored temporarily by contact with a stimulator-tip at about 45° , but a secondary slump quickly follows even with mild stimulation.

(2) *Field-temperature gradually raised.* When the temperature of the field is slowly increased, no such simple and consistent result is obtained. Instead a variety of effects may occur. In Fig. 5 B, C, and D are shown detail records of three typical reactions.

In the first type of reaction (Fig. 5 B), the liminal temperature of the spot rises to a certain maximum value, as the field-temperature is increased. This was 37° to 38° for *Sa*; somewhat lower for the other *Os*. This rise was the expected result, on the basis of the findings of Goldscheider²³ and Siebrand²⁴ who showed that the liminal temperature for cold could be raised by pre-warming the skin. The maxima obtained in the present study are somewhat higher than those given by these two experimenters.

Less expected was the second type of reaction (Fig. 5 C). That is, as the field-temperature rises, the liminal temperature of the spot rises initially, only later to reverse its trend and eventually come back approximately to where it started. This gives a definite indication that the effect on the limen is not a simple matter, but possibly the resultant of two or more influences.

²³ Goldscheider, Beiträge zur Lehre von der Hautsensibilität, *Zsch. f. klin. Med.*, 74, 1912, 283.

²⁴ Siebrand, *op. cit.*, 208.

Totally unexpected was the third type of reaction (Fig. 5 D). In this case, there is no rise of the liminal temperature at all. Instead, as the field-temperature is increased, the liminal temperature goes steadily downward until finally the spot may fail to respond even to 10° . Now if the field-temperature is gradually brought back to 33° , the liminal temperature

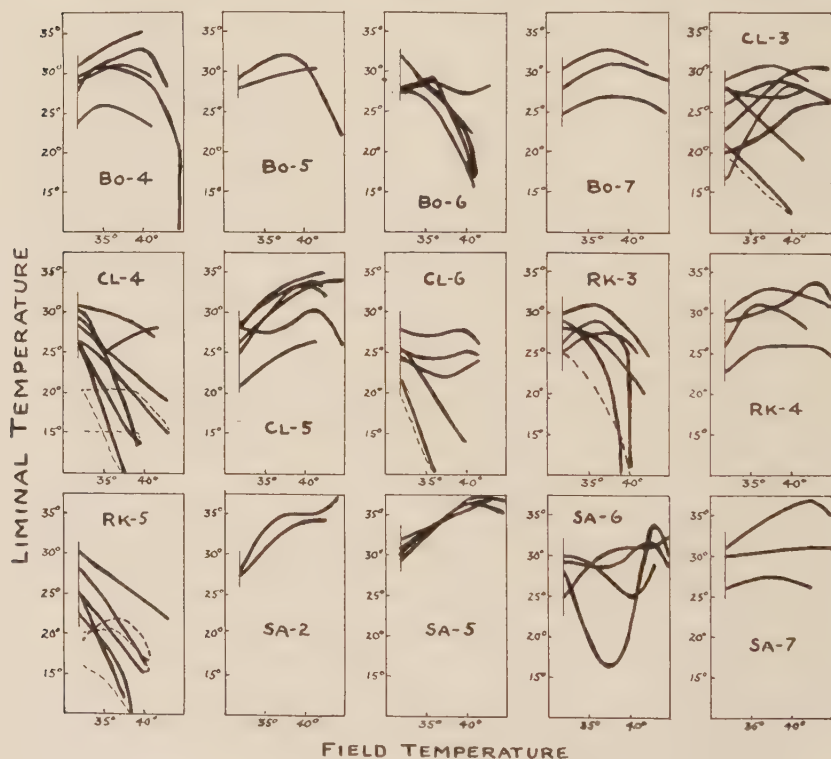


FIG. 7. EFFECTS OF RAISED FIELD-TEMPERATURE ON DIFFERENT COLD SPOTS

climbs again practically to its original value, as is shown by the dotted lines in Fig. 5 D and Fig. 7. This indicates that the depression is specific to the increase in field-temperature and cannot be ascribed merely to general fatigue. Apparently the downward trend starts as soon as the field becomes a degree or two warmer than normal, and continues without any sign of a critical level, such as was found in the case of lowered field-temperature.

Fig. 7 shows the effect of increased field-temperatures in a number of cold spots. Every curve in this figure is derived in a manner similar to those

shown in detail in Fig. 5. Notice that the general type of reaction seems fairly characteristic of the spot itself. For instance, *Bo-6*, *Cl-4*, *Rk-3*, and *Rk-5* consistently show the third type of reaction, *i.e.* depression. *Cl-5*, *Sa-2*, and *Sa-5* are rather consistent in showing the first type of reaction, *i.e.* elevation. Marked inconsistency, however, is found in spot *Cl-3*, where each of the three types of reaction was observed, several times apiece, on different occasions. It will be noticed that *Cl-3* was also highly variable in the levels of its normal limen and in its reactions to low temperatures.

It is interesting to note that ordinarily the *O* never felt any temperature sensation from the field disk, although the rise was often as rapid as 1° per min. Above 45° prickling sensations usually set in, which interfered seriously with temperature discrimination. This accounts for the absence of systematic determinations above this level.

DISCUSSION

(1) *A working hypothesis.* During the course of this investigation, it was found helpful to postulate a mechanism which would account for the observed phenomena and act as a guide for further research. Thus the following working hypothesis was found fruitful.

(a) Depression and restoration of the liminal temperature suggest as a basic mechanism a reversible reaction: $A \rightleftharpoons B$. This reaction proceeds rapidly in the direction $A \rightarrow B$ (depression) under the influence of a low temperature; and more slowly in the direction $B \rightarrow A$ (restoration) upon removal of the low temperature. The latter reaction can be speeded up by the application of a higher temperature (*i.e.* from 40° to 46°). This is not necessarily a chemical reaction, although it is convenient to think of it as such, because of its resemblance to the reactions of visual purple. Thus the bleached state of visual purple (low sensitivity) corresponds to the state B of our hypothetical cold receptor mechanism, and the purple state (high sensitivity) to state A. In both instances, the reaction proceeds rapidly in one direction and more slowly in the other. Whether the restoration of visual purple can be speeded up in any way is not known (to parallel the rapid restoration of $B \rightarrow A$ by high temperatures).

(b) The liminal temperature depends upon the state of balance existent in $A \rightleftharpoons B$ at the moment. The further the reaction has proceeded in the direction $A \rightarrow B$, the lower the temperature must be for stimulation. (Similarly with visual purple: the further it has moved toward the bleached state, the stronger the light must be to stimulate.) From the standpoint of liminal temperature, then, adaptation involves primarily a shift in the equilibrium of $A \rightleftharpoons B$ to some new level. (Likewise with visual purple, adaptation involves a similar change.)

(c) The sensation of cold results when the reaction moves in the direction $B \rightarrow A$, at a rate faster than some necessary minimum. (At this point, we must drop the analogy to visual purple.) Within limits, the more rapid the change, the more intense would be the resulting cold experience. The duration of the sensation depends upon the duration of the change, the experience of cold ceasing when move-

ment in the direction $A \rightarrow B$ ceases. It is evident that the change might last longer than the actual contact of the stimulating object, thus accounting in part for after-sensations.

(d) Such a simple reversible reaction, however, does not account for the facts of *stability*. It will be recalled that a cold spot may show a relatively high initial liminal temperature and yet 'fade' rapidly under stimulation. This suggests the presence of a substance 'C' which is used up during the restorative process. Assume that in 'fading' spots, very little 'C' is present; whereas stable spots have an ample reserve of it. Then it becomes apparent why two cold spots with the same initial liminal temperatures may behave quite differently upon repeated just-liminal stimulation. The supply of 'C' is quickly used up in the weak spot and restoration is no longer possible. Since even the weakest spots eventually recover, it seems probable that 'C' is slowly renewed or regenerated, possibly through the agency of the blood stream.

(e) This $A \rightleftharpoons B$ and C theory was developed on the basis of experiments with the field-temperature maintained at 33° . How well does it explain the results obtained when the field-temperature was varied? The effects of gradually lowering the field temperature seem to fit in quite smoothly. The initial change in liminal temperature is readily explainable as a shift in the balance of $A \rightleftharpoons B$. Then it is only necessary to assume that the lowered field temperature acts adversely upon 'C' as well, and markedly so below a certain critical level. The reserve of 'C' becomes so depleted that there is not enough of it to take care of the restorative action, and hence the liminal temperature plunges sharply downward.

(f) The varied effects of gradually raising the temperature of the field are more troublesome. High temperatures, according to the theory, should cause the reaction to move in the direction $B \rightarrow A$, resulting in a higher liminal temperature. This is what occurs in the first type of reaction. But what of the other two types, where there is definitely a downward trend? These curves might be explained as *resultants* of opposed effects upon $A \rightleftharpoons B$ and 'C'. Thus, under some circumstances, the liminal temperature might be expected to move downward, because a depleted supply of 'C' cannot fully restore the reaction $A \rightleftharpoons B$ to its former equilibrium after each testing stimulation. To duplicate the curves empirically obtained, however, it is necessary to assume a nicety of balance in these opposed effects that is scarcely credible. Perhaps it is better to let the explanation of these effects wait upon further critical evidence.

(g) It will be noticed that no attempt has been made to account for paradoxical cold in terms of this theory. Originally, it was expected to assign paradoxical cold to a very rapid restoration of $B \rightarrow A$, on the ground that *any* change in equilibrium might produce a sensation if it were rapid enough. None of the *Os*, however, experienced paradoxical cold under the conditions of this experiment. To assign the sensations actually reported (hot, warm, and non-thermal) to the restoration phase of $B \rightarrow A$ would involve a revision of the doctrine of specific energies, which is too radical a procedure to be justified by the present evidence. On the other hand, the data of this experiment present no justification for explaining paradoxical cold on such a basis.

(2) *Problem of larger areas.* One fact, however, is plainly evident from the results of this study. The thermal sensitivity of larger areas cannot be

explained as a simple arithmetical addition of individual temperature spots. If this were so, one should be able to step under a cold shower, feel a brief burst of cold, and all would be neutral. At least, that is the way a single cold spot appears to act.

Thus, if the current theory of punctiform thermal sensitivity is to be upheld, the cold spots must operate upon some 'united we stand, divided we fall' principle. Just how this could be, it is not safe to speculate upon at the present time, but certainly, bridging the gap between the effects in single spots and in larger areas presents a fascinating field for further research.

This study offers little support for Nafe's ingenious theory that warm and cold sensations are to be explained as kinesthetic patterns from dilating and contracting blood vessels.²⁵ It is almost incredible that blood vessels could be expected to exhibit such a complicated cycle of reactions. The assumption of some sort of a definite receptor mechanism (possibly a physiological rather than an anatomical entity) seems to be a much more fruitful hypothesis.

SUMMARY

With a procedure which permitted pure thermal stimulation (touch excluded) of single cold spots, surrounded by a field of controllable temperature, the following effects were observed on the left forearms of 6 Os.

(1) When a single cold spot was stimulated continuously at a constant temperature, the cold sensation usually died out entirely in less than 4 sec.

(2) Following continuous or intermittent stimulation at low temperatures, there was a long-lasting depression of the liminal temperature. Even with just-liminal stimulation, some cold spots 'faded out' completely after a few stimulations at 30-sec. intervals.

(3) Rapid restoration of the liminal temperature could be effected by one minute's contact with high temperatures, but such recovery was apt to be unstable when the depression had been extreme. Rest periods of 2-5 min. also brought about very unstable recovery.

(4) Under the conditions of the experiment, paradoxical cold was not experienced by any of the 6 Os, with stimulation at high temperatures. Instead, there were frequent reports of 'hot' and 'warm' when the cold spot was stimulated with temperatures about 45°.

(5) The reaction-time to stimulation of a single cold spot varied from O to O, but seemed to bear no direct relation to the stimulating tempera-

²⁵ J. P. Nafe, The pressure, pain and temperature senses, in Murchison's *Handbook of General Experimental Psychology*, 1934, 1054-1058.

ture. The reaction-times were considerably longer than those reported in the literature from stimulating of larger areas.

(6) When the temperature of the field surrounding the cold spot was gradually reduced, the liminal temperature held its own relatively until the field reached a certain critical temperature (from 28° to 22°). Then the liminal temperature dropped sharply until the spot would no longer respond even to 10° .

(7) When the temperature of the surrounding field was gradually raised, three different effects were observed: (a) the liminal temperature rose to a certain maximum; (b) there was an initial rise followed by a fall to about the original level; (c) there was no rise whatever, but the liminal temperature fell steadily as the field-temperature rose, and rose again if the field temperature was brought back to normal.

(8) To account for the elevation and depression of the liminal temperature, a reversible reaction $A \rightleftharpoons B$ is suggested, which bears some resemblance to the reversible reaction of visual purple. To cover the facts of stability and instability, an accessory substance 'C' is postulated. This is present in different spots in varying amounts, and is used up in bringing about the restoration phase $B \rightarrow A$. Such a mechanism explains reasonably well the results secured in this study of single cold spots. Bridging the gap between these effects and those traditionally secured with larger areas is left for further research.

